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ATMOSPHERIC CARBON DIOXIDE AND CLIMATE

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ATMOSPHERIC CARBON DIOXIDE AND CLIMATE

Mikhail Ivanovich Budyko

The influence of changes in carbon dioxide concentration /2*
on the thermal regime of the atmosphere is considered, taking into account the interrelationship between air temperature and the configuration of the polar ice. It is made clear that relatively small fluctuations in the amount of carbon dioxide can substantially change climatic conditions on our planet. The dependence found between the carbon dioxide content of the atmosphere and thermal conditions is used in discussing the laws governing climatic changes.

The study is of interest to meteorologists, geographers, and geologists.

1. CARBON DIOXIDE IN THE ATMOSPHERE /3

Carbon dioxide gas, often called carbon dioxide in meteorology, is one of the relatively minor components of atmospheric air in quantity. In the current epoch the atmosphere contains about $2.3 \cdot 10^{12}$ (metric) tons of carbon dioxide, which comprises 0.032% of all atmospheric air (percent by volume).

A significantly larger amount of carbon dioxide is contained in the hydrosphere, where (mainly in ocean waters) about $130 \cdot 10^{12}$ tons of carbon dioxide are dissolved. Between the atmosphere and the hydrosphere a constant exchange of carbon dioxide is carried on by means of molecular and turbulent diffusion.

*Numbers in the margin indicate pagination in the foreign text.

Measurements of carbon dioxide concentration in the atmosphere show that it varies little in the different geographical regions and, likewise, with height within the trophosphere. The relatively constant content of carbon dioxide gas in the atmosphere in comparision with water vapor is explained by the lesser variability in intensity of the sources and sinks for carbon dioxide gas at the surface of the earth and by the absence of a significant dependence of the content of carbon dioxide on temperature. From the data of observations it follows that the concentration of carbon dioxide gas increases somewhat in the equatorial zone and decreases in size about 0.005% in the high latitudes. This change is explained by the higher solubility in the cold ocean waters of the high latitudes in comparison with the warm waters of the tropics. As a result of this, at high latitudes the atmosphere loses a portion of the carbon dioxide which is dissolved in the oceans, where the excess of carbon dioxide gas is transported by deep cold currents to the low latitudes, after which it is returned to the atmosphere. The magnitude of the flux of carbon dioxide resulting from this mechanism between the equator and the north pole amounts to about $2 \cdot 10^{10}$ tons/year (Bolin and Keeling, 1963).

Along with the exchange of carbon dioxide between the atmosphere and the ocean there is a constant exchange of carbon dioxide gas between the atmosphere and the hydrosphere, on the one hand, and living organisms and the lithosphere on the other. This cycle possesses exceptional significance for the maintenance of life on our planet.

The main components of the carbon dioxide cycle are deter- /4
mined by biological processes. Carbon dioxide gas is absorbed by autotrophic plants during photosynthesis, which directly or indirectly supplies the overwhelming majority of living organisms

with energy. In the course of the vital activity of these organisms (in particular, in the process of breathing) carbon dioxide is returned to the atmosphere and the hydrosphere.

A definite quantity of carbon dioxide enters into the atmosphere from the depth of the earth's crust, from which it emanates during volcanic eruptions, from mineral sources, and so forth. Carbon dioxide is consumed in the process of weathering of siliceous rocks and in the formation of various carbon compounds.

Thus, in the balance of atmospheric carbon dioxide there are two cycles, biological and geological, in each of which delivery and consumption of carbon dioxide gas takes place. Available data shows that the biological components of the annual cycle of carbon dioxide significantly exceed the geological.

The consumption of carbon dioxide gas in photosynthesis for a year amounts to approximately 10^{11} tons. Just as much carbon dioxide is formed in the process of breathing and as a result of the decomposition of living organisms. From the depth of the earth's crust comes a significantly smaller quantity of carbon dioxide - approximately 10^{8} tons. The same quantity of carbon dioxide in order of magnitude is consumed in various geological processes (Plass, 1956; Mueller, 1960; Lieth, 1963 et al.).

Living organisms, products of their vital activity and of the lithosphere contain great quantities of carbon, obtained from the atmosphere and from the hydrosphere in the form of carbon dioxide gas. The amount of carbon in living organisms apparently corresponds roughly to 10^{12} tons of carbon dioxide gas (estimates of this value by various authors notably differ - see Takahashi, 1967; Man's Impact on the Global Environment, 1970, etc.).

The quantity of carbon in the lithosphere corresponds roughly to $2 \cdot 10^{17}$ tons of carbon dioxide, the principal part of which is bound in carbonate rocks (Vinogradov, 1972).

Although the estimates of the components of the carbon dioxide balance and of the reserves of carbon in various natural media presented here have a very approximate character, it is possible to make several deductions from them about the rates of the carbon dioxide cycle.

Thus, in particular, living organisms have a comparatively small "carbon dioxide capacity": the carbon in them is renewed in a comparatively short time, amounting on the average to around 10 years. The average time of renewal of carbon in the atmosphere amounts to roughly 20 years. The period during which the buildup of carbon in the lithosphere took place is very great and comparable to the duration of the existence of the biosphere.

There is a basis for supposing that in the geological past the concentration of carbon dioxide in the atmosphere significantly differed from its modern value. It follows from this that the total of all forms of delivery of carbon dioxide gas to the atmosphere and its consumption was on many occasions not equal to zero. /5

One can conclude, however, that the departure of this total from zero year by year comprised a very small part of the absolute magnitude of the main members of the balance of atmospheric carbon dioxide gas. Thus, for example, if we assume that for the last million years the concentration of carbon dioxide in the atmosphere diminished by a factor of two, this will correspond to a change in its value per year by a quantity equivalent to 0.002% in all of the annual magnitude of photosynthesis.

According to the ideas of A. P. Vinogradov (1967 et al), atmospheric carbon dioxide, along with several other gases of the atmosphere, arose in the course of zonal melting of the mantle of the earth, heated as a result of decay processes of radioactive elements. In Proterozoic time the atmosphere was anaerobic and contained a large quantity of carbon dioxide gas. With the end of the Proterozoic the composition of the atmosphere began to change under the influence of photosynthesis. Then the quantity of oxygen was gradually increasing, and the atmosphere was acquiring an oxidative character. The increase in oxygen content was accompanied by a diminishing of the carbon dioxide concentration.

In the works of A. B. Ronov (1959, 1964, 1972) there are considered the mechanisms of change in quantity of carbon dioxide gas in the atmosphere in the geological past. As was established in these investigations, in the Paleozoic and the Mesozoic the concentration of carbon dioxide gradually diminished, mainly as a result of the consumption of carbon dioxide gas in the formation of carbonaceous rocks. In the epoch of heightened volcanic activity the quantity of carbon dioxide in the atmosphere increased slightly.

Estimates of the concentrations of atmospheric carbon dioxide in the various geological periods have a very approximate character. In particular, there is a proposal that the concentration of carbon dioxide gas in the Permian period (around 200 million years ago) totalled 7.5% (Hoffman, 1951). Proceeding from this estimate, it is possible to conclude that in the Mesozoic and Cenozoic the average rate of decrease in concentration of carbon dioxide amounted to about 0.04% for a million years.

In the modern epoch the process of reduction in the concentration of atmospheric carbon dioxide was replaced by a process of its rapid increase. The hypothethis that, as a result of the burning of large quantities of coal, oil, and other forms of fuel, the quantity of carbon dioxide gas in the atmosphere began to increase, was stated already in the first half of the 20th century (Callender, 1938). But only in the fifties, in connection with the organization of the International Geophysical Year, were systematic observations of atmospheric carbon dioxide started at a series of stations which permitted the quantitative estimation of the increase of carbon dioxide concentration.

These observations showed that, along with a marked annual variation in the concentrations of carbon dioxide at the earth's surface (decrease of concentration in summer in connection with the intensification of photosynthesis), there was a distinct tendency toward increase of concentration from year to year. According to the results of observations at Mauna Loa (Hawaiian Islands) for the period from 1958 to 1968, the yearly increase of concentration of carbon dioxide amounted to $0.64 \cdot 10^{-4}$%. This amount corresponds to half of the quantity of carbon dioxide annually entering the atmosphere as a result of the burning of various forms of fuel (Inadvertent Climate Modification, 1971). /6

The results of observations at Mauna Loa are in agreement with the data of analogous observations in Alaska, Switzerland, and Antarctica. Taking into account that these observations were carried out in regions of the terrestrial orb widely separated from each other, it cannot be doubted that they correctly reflect a present-day tendency of change in concentration of atmospheric carbon dioxide.

From the data of the indicated observations it follows that there is retained in the atmosphere approximately half of the carbon dioxide gas formed as a result of the activity of man. The second half of this quantity is apparently absorbed by the ocean and the biosphere.

The question of the mechanism of absorption of the additional carbon dioxide by reservoirs and living organisms in quantitative plan is insufficiently studied. Although the oceans potentially have a large capacity and can absorb an immense quantity of carbon dioxide gas, the actual rate of absorption of carbon dioxide by marine waters is signficantly reduced because of the slow exchange between the surface and deep layers of the oceans.

With an increase in carbon dioxide concentration the rate of photosynthesis increases; however, the additional quantity of organic matter created because of this is mineralized in a limited time, releasing the carbon dioxide gas expended in its formation.

The construction of a completely quantitative theory which permits taking into account the effects of buffering processes in the ocean and the biosphere is a task for the future.

At present for this end one can make use of empirical models, an example of which is the simple numerical model being proposed by L. Machta, Ya. Makhta, and D. Olson (Man's Impact on the Global Environment, 1970). From computations with this model it follows that, by the year 2000, the concentration of carbon dioxide gas will increase from 0.032 to 0.038 %, i.e., almost by 20% compared with its current value.

Using this model it is possible also to find that, a hundred years ago, before the beginning of an epoch of rapid industrial development, the concentration of carbon dioxide in the atmosphere was approximately 0.029%, i.e., lower than the current magnitude by 10% (Inadvertent Climate Modification, 1971).

Let us dwell on the problem concerning the influence that the concentration of atmospheric carbon dioxide exerts on living nature. /7

The vegetative cover of the land fundamentally consists of autotrophic plants that manufacture organic matter out of atmospheric carbon dioxide gas and take from the soil water and mineral substances. Along with atmospheric carbon dioxide, plants can utilize also solid carbon dioxide, but its quantity is usually insignificant in comparison with the carbon dioxide received from atmospheric air. Autotrophic plants in the hydrosphere utilize carbon dioxide dissolved in the water in photosynthesis.

It has already been long established that with a more or less adequate supply of radiation and with other conditions favorable for photosynthesis, its rate is significantly limited by low content of carbon dioxide gas in the atmosphere and in bodies of water.

Numerous experiments indicate that increases in the concentration of carbon dioxide, other conditions being equal, make possible a significant rise in the rate of photosynthesis.

For the majority of plants, the rate of photosynthesis rises with an increase of the concentration of carbon dioxide up to several tens of percent. Then this increase in the rate of photosynthesis comes to a stop, and, with concentrations a few percent, higher photosynthesis begins to decline.

A considerable increase in photosynthesis with elevated carbon dioxide concentrations is often interpreted as evidence of the adaptation of autotrophic plants in the course of their evolutionary development to the much higher concentrations of carbon dioxide that were present in the past. Since the findings of geochemical investigations are interpreted as a gradual diminishing in the course of the last hundred million years of the quantity of carbon dioxide in the atmosphere, such a hypothesis can be considered plausible.

In this connection there arises the question: could the concentration of carbon dioxide in the atmosphere during the epoch of existence of autotrophic plants have exceeded the value at which the rate of photosynthesis begins to diminish? It is quite difficult to answer this question, since the dependence of photosynthesis on the quantity of carbon dioxide for plants of the distant past does not necessarily coincide with the analogous dependence for present-day plants.

Let us note that a change in concentration of carbon dioxide in the atmosphere exerts an influence on the combined mass of living organisms existing on our planet. A considerable portion of this biomass consists of the substance of autotrophic plants, whose quantity is governed by the amount of their photosynthesis. The following simple law rests on the basis of this regulation. The consumption of the organic substance of autotrophic plants in respiration, the dying out of separate organs of the plant, etc. can be taken to be proportional to the mass of the plant. Taking into account that the total magnitude of photosynthesis is equal to the consumption of organic substance, the rate of photosynthesis, being in a first approximation, proportional to the concentration of carbon dioxide, we find that the mass of plants is proportional to the concentration of carbon dioxide gas.

One may think that, in some cases, the dependence of the mass of plants on the concentration of carbon dioxide is weaker, /8
because with an increase of plant cover the rate of photosynthesis can grow. But for a continuous vegetative cover at the time of its optimum structure yielding the maximum productivity, the

dependence of total photosynthesis on the dimensions of the photosynthesizing cover is slight.

In this way the mass of autotrophic plants depends essentially on the carbon dioxide concentration, this dependence having in a number of cases the character of direct proportionality.

It is obvious that this conclusion applies basically to conditions when the water regime, mineral nourishment, and other factors are not "at a minimum," i.e., they do not essentially limit photosynthesis. One may think, however, that even in the presence of factors limiting photosynthesis there is a definite relation between plant mass and carbon dioxide concentration, which appears especially noticeable at small concentration magnitudes.

From the conclusions presented it follows that in the geological past, when the concentration of carbon dioxide gas in the air was signficantly larger than today, the mass of vegetative cover on the land exceeded its figure. This chiefly concerns vegetative zone of adequate moisture supply. The total magnitude of the biomass of autotrophic plants in the oceans during the epoch of high carbon dioxide content similarly could have been larger than its present-day value.

Thus, the process of reduction of the carbon dioxide concentration in the atmosphere (and) in the hydrosphere was evidently accompanied by a gradual reduction in the mass of autotrophic plants and, consequently, of all the masses of living organisms on our planet.

From the mechanism established above it follows that, for every plant of a specified size, there is some lower limit of carbon dioxide concentration, which upon being reached, makes the existence in the given plant impossible. With a reduction of carbon dioxide concentration, autotrophic microorganisms might exist the longest of all, having a minimal relation of their mass to the dimensions of the photosynthesizing cover.

One can pose the question: How rapidly would this change in the biosphere occur if the earlier existing tendency of diminishing carbon dioxide persisted into the future? It was mentioned above that from the available data the average rate of reduction in carbon dioxide concentration for the last 200 million years was roughly equal to 0.04% per million years. Since the present value of the concentration of atmospheric carbon dioxide comprises about 0.03% of the whole, it seems possible to draw the conclusion that the extinction of autotrophic plants will happen in the course of a million years, i.e., in a very short period in comparison with the duration of its existence.

Such a conclusion, however, would be inadequately founded. In the first place, as shown below, the rate of reduction in carbon dioxide concentration during the Pleistocene was apparently /9
smaller than the values presented here. In the second place, most recently as a result of man's activity, the decrease in the concentration of carbon dioxide gas came to a halt and changed to an increase. Thirdly, there are grounds for reckoning that, if the process of reduction of the quantity of atmospheric carbon dioxide had continued longer, then long before the extinction of autotrophic plants due to the lack of carbon dioxide, an abrupt change in climatic conditions would occur, which would make further existence of life on earth impossible.

The question of the effect on climate of a change in the concentration of atmospheric carbon dioxide is considered in the following sections of this study.

2. ATMOSPHERIC CARBON DIOXIDE AND CLIMATIC CHANGE

Over a hundred years ago Tyndall showed that, since atmospheric carbon dioxide along with water vapor absorbs long-wave radiation in the atmosphere, changes in concentration of carbon dioxide could lead to fluctuations in climate (Tyndall, 1861). Subsequently, the question of the effect of atmospheric carbon dioxide on climate attracted the attention of Arrhenius (1896, 1903) and Chamberlin (1897, 1898, 1899), who proposed that changes in the quantity of atmsopheric carbon dioxide could have been the cause of the Quaternary glaciations. In the works of Arrhenius the absorption of radiative flux in the atmosphere was investigated, and a numerical model was proposed for the determination of temperature at the earth's surface as a function of atmospheric properties. Using this model Arrhenius found that an increase of the quantity of carbon dioxide gas by 2.5 - 3 times raises the temperature of the air by 8 - 9°, and a reduction of the quantity of carbon dioxide by 38 - 45% lowers the temperature by 4 - 5°.

Bearing in mind the details of geological investigations, Arrhenius noticed that the quantity of carbon dioxide in the contemporary atmosphere comprised a small portion of the carbon dioxide gas which in the past was absorbed from the atmosphere and consumed in the formation of carbonaceous rocks. In this connection Arrhenius concluded that the concentration of carbon dioxide in the atmosphere could vary by broad limits. These changes, in the opinion of Arrhenius, exerted a significant influence on the air temperature, sufficient for the emergence and disappearance of glaciation.

Chamberlin's research was devoted chiefly to the geological side of this problem, considering the balance of atmospheric carbon dioxide, Chamberlin noticed that the inflow of carbon dioxide gas from the lithosphere changed significantly depending upon the level of volcanic activity and other factors.

The consumption of carbon dioxide gas in geological processes likewise strongly varied, in particular, in correlation with the magnitude of the rock surface exposed to the action of atmospheric erosion. With the increase of this surface the consumption of /10
carbon dioxide determined by the process of weathering grew.

Chamberlin supposed that glaciation arose as a result of an intensive process of mountain building and raising of the level of the continents, which led to an increase in the base for erosion, growth of the rock surface being eroded, and a reduction in the concentration of carbon dioxide in the atmosphere. To support this assumption Chamberlin carried out several computations which, however, could not be considered as any kind of complete numerical model of the process being studied.

Subsequently the carbon dioxide hypothesis origin of the Quaternary glaciations was subjected to doubt because it was ascertained that in the radiation absorption band of carbon dioxide gas corresponding to a wavelength of 13-17 micrometers, notable absorption of radiation by water vapor occurred, which reduced the influence of changes of carbon dioxide concentrations on the thermal regime.

Taking into account the influence of this effect, Callender (1938) obtained smaller magnitudes of change in temperature at the earth's surface with fluctuations of carbon dioxide concentrations compared with Arrhenius's results. According to Callender's findings, doubling the quantity of carbon dioxide gas raised the air temperature by 2°, the influence of the change in carbon dioxide concentration on temperature being reduced with increase of concentration.

In Callender's works (1938 et al.) the proposition was stated that the warming of the climate in the first half of the 20th century was connected with the rise in concentration of carbon dioxide in the atmosphere due to man's industrial activity.

Although Callender demonstrated the great significance of calculating the absorption of long wave radiation by water vapor for a correct estimate of the influence of a change in carbon dioxide concentration on temperature, nevertheless Plass (1956) and Kaplan (1960) completed calculations of the influence of carbon dioxide on the thermal regime without allowing for this effect. Plass obtained sufficiently large changes of temperature at the earth's surface (a rise in temperature of 3.6^{O} by doubling the carbon dioxide concentration, a decrease of 3.8^{O} by halving the concentration) to allow him to return to the carbon dioxide hypothesis for the origin of the Quaternary glaciations. For substantiation of this hypothesis, Plass advanced the concept of the self-oscillating character of changes of carbon dioxide concentration in the atmosphere and ocean, which reduces to the following.

After an initial small reduction in the quantity of carbon dioxide in the atmosphere there occurs a reduction in the temperature at the earth's surface that gives rise to an increase of the mass of polar ice. The volume of oceanic waters is diminished as a result, which leads to an increase in the content of carbon dioxide in the atmosphere and a new warming. After the onset of warming thaws the ice, the volume of the oceans grows, the quantity of carbon dioxide in the atmosphere diminishes, and a new period of cooling begins.

In Kaplan's work it was observed that the influence of /11
the cloud cover markedly reduces the change of temperature at the earth's surface determined by fluctuations of carbon dioxide concentration, compared with the estimate obtained by Plass.

The necessity of allowing in computation of the influence of carbon dioxide on the thermal regime of the atmosphere for the absorption of long wave radiation by water vapor was emphasized in the investigations of K. Ya. Kondrat'ev and Kh. Yu. Niylisk (1960) and in the work of Moller (1963). Taking this effect into account, K. Ya. Kondrat'ev and Kh. Yu. Niylisk obtained much smaller changes of temperature at the earth's surface compared with the results of Plass and Kaplan.

Moller considered that, with changes of air temperature, the absolute humidity of the air usually changes, whereas the relative humidity remains more or less constant. An increase in the absolute humidity of the air with a rise in temperature strengthens the absorption of long wave radiation in the atmosphere, which further raises the temperature. Moller found that the increase of temperature at the earth's surface determined by doubling the concentration of carbon dioxide at constant absolute humidity amounted to 1.5°, whereas at constant relative humidity, this value increase by several times. Besides this Moller noticed that the influence of carbon dioxide on the thermal regime can be offset by comparatively slight changes of the absolute humidity of the air or of cloudiness.

A detailed investigation of the dependence of air temperature on carbon dioxide concentration in the atmosphere was completed by Manabe and Wetherald (1967). In this work there was noted the inaccuracy of the computations of Moeller, who estimated changes of the thermal regime of the atmosphere only by data on the thermal balance of the earth's surface, not considering the balance of the atmosphere as a whole.

Manabe and Wetherald computed the vertical distribution of temperature in the atmosphere, allowing for absorption of long wave radiation by water vapor, carbon dioxide gas, and ozone. In the computation there was used the vertical distribution of relative humidity given by empirical findings. It was assumed that the distribution of temperature is determined by conditions of local radiative equilibrium if the vertical gradient of temperature does not exceed 6.5°/km. The indicated value of the temperature gradient was regarded as the maximum possible because of the limiting influence of convective processes on an increase of the vertical gradient.

Manabe and Wetherald found that, for average conditions of cloudiness, doubling the concentration of carbon dioxide gas at constant relative humidity increased the temperature at the earth's surface by 2.4°. Halving the existing concentration lowered the air temperature by 2.3°.

In subsequent works by Manabe calculations were made of the influence of changes in carbon dioxide concentration on air temperature at various latitudes. Using a three-level model of the general circulation of the atmosphere, Manabe found that the rise of temperature at high latitudes due to an increase in carbon dioxide concentration exceeded by roughly a factor of two the rise in average global temperature (Inadvertent Climate Modification, 1971). /12

Changes in air temperature at various latitudes for a large range of carbon dioxide concentrations were calculated by L. R. Rakipova and O. N. Vishnyakova (1973). For the solution of the problem posed in this work a two-level model of the thermal regime of the atmosphere was used, including an account of the radiative fluxes of heat, the supply and withdrawal of heat with condensation and evaporation, macroturbulent heat exchange in the atmosphere, and the heat exchange between the surface of the ocean and low-lying layers. In computing the radiative fluxes the influence of water vapor and ozone was taken into account.

L. R. Rakipova and O. N. Vishnyakova calculated changes of air temperature for various latitudes and different heights as a function of the concentration of carbon dioxide gas, which varied from zero to a value exceeding by 5 times its present-day value. Calculations were done for the cold and warm halves of the year, under conditions of a cloudless atmosphere and for average conditions of cloudiness. The influence of the cloudcover on the relation of air temperature with concentration of carbon dioxide gas proved to be comparatively slight. Differences in this dependence for the hot and cold halves of the year likewise turned out quite small.

The dependence of the average global temperature at the earth's surface for average annual conditions on the carbon dioxide concentration determined by L. R. Rakipova and O. N. Vishnyakova is illustrated in Fig. 3 in the form of a dashed line. As is evident in this figure, the air temperature at the earth's surface decreases by 6 - 7° with a reduction of the concentration to zero, and rises roughly by 2° with an increase of concentration by 3 - 4 and more times compared with its contemporary level.

It must be noted that L. R. Rakipova and O.N. Vishnyakova, in contrast to Manabe and Wetherald, assumed that with changes of carbon dioxide concentrations the absolute humidity of the air remains constant. This assumption implies that changes in evaporation with changes of temperature at the earth's surface are negligible in effect, which leads, as was shown by Manabe and

Wetherald, to some underestimating of the changes of air temperature due to fluctuations of carbon dioxide concentration.

All the investigations referred to above on the influence of change in carbon dioxide concentration on the thermal regime of the atmosphere contain a great number of simplifying assumptions. In the majority of these investigations the problem is considered a local one, without accounting for possible changes on the general circulation of the atmosphere as a result of changes in air temperature.

From this point of view the recent works by Manabe and /13 the investigations by L. R. Rakipova and O.N. Vishnyakova are of interest, from which it follows that the computation of the temperature changes at various latitudes gives results for average global conditions not differing very greatly from a calculation made directly from data averaged for the planet as a whole.

It was already repeatedly noted that temperature changes due to fluctuations in the quantity of carbon dioxide can depend on associated changes in the cloud cover regime. Although recently obtained results showing that the influence of changes in cloudiness on the temperature at the earth's surface in a series of cases is not significant (Budyko, 1971), this question is obviously required in a future investigation.

Of the various limitations accepted in earlier completed investigations of the effect of the quantity of carbon dioxide gas on climate, one of the most significant, from our point of view, is the direct inverse connections between the thermal regime of the atmosphere and the area of polar ice cover. This effect was partly allowed for in the latest works of Manabe (Inadvertent Climate Modification, 1971), which took into account changes in the area of snow cover as a function of the thermal regime of the atmosphere. As a result Manabe obtained more significant changes of air temperature (in particular for the higher latitudes) with fluctuations of carbon dioxide concentration in the atmosphere.

The study of the influence of changes in area of the polar ice cover on the connection of carbon dioxide concentration with the thermal regime is of interest.

From general considerations it follows that fluctuations of the area of polar ice can intensify changes in the thermal regime resulting from the significant influence of the ice cover on the earth-atmosphere system. Calculations made earlier show that such an influence intensifies by several times changes in the average planetary temperature at the earth's surface due to fluctuations in the flux of radiation at the lower boundary of the atmosphere (Budyko, 1968).

It is evident that the question of the influence of changes of carbon dioxide concentration on the thermal regime is closely connected with the question of the degree of stability of the contemporary climate, i.e, of the possibility of its significant change with small fluctuations in the climate-producing factors.

3. STABILITY OF CLIMATE

For the study of the question of the stability of the thermal regime in the contemporary epoch it is necessary to make use of a numerical model of the distribution of temperature in the atmosphere, in which the main factors influencing the thermal regime are taken into account. In the elucidations of these factors one must take into consideration the thermal regime of the lower layers of the atmosphere is determined to a significant degree by the long wave radiations going to outer space, /14 which is basically formed within the limits of the troposphere. The dependence between temperature at the earth's surface and outgoing radiation was established in a series of theoretical and empirical investigations (Manabe and Wetherald, 1967; Budyko, 1968, et al.).

The amount of outgoing radiation is the algebraic sum of all the other components of the heat balance of the earth-atmosphere system, including absorption of solar radiation, the buildup and dissipation of heat in this system, and the horizontal redistribution of heat in the atmosphere and ocean due to circulation processes. This redistribution is basically determined by the transport of heat in the troposphere and in a comparatively thin upper layer of the oceanic waters. As available estimates show, for wide belts the buildup and dissipation of heat in the earth-atmosphere system in the course of a year depends little on the heat exchange in the atmosphere and upper layers of the soil, and is determined chiefly by thermal processes in the upper layers of the ocean.

The average latitudinal magnitudes of the enumerated components of the heat balance of the earth-atmosphere system are presented in Table 1, compiled from the findings of investigations of the heat balance made at the Main Geophysical Observatory.

In this table Q_a is the solar radiation absorbed in the earth-atmosphere system, A_1 and A_2, the redistribution of heat as a result of circulation processes in the atmosphere and in the ocean respectively, B, the change in heat content of the upper layers of the ocean, I_s, the long wave radiation going out to outer space. All quantities are expressed in $\mathrm{kcal \cdot cm^{-2} \cdot month^{-1}}$, positive values corresponding to inflow of heat and negative, to outflow.

Table 1*

HEAT FLUX AT VARIOUS LATITUDES (kilocalories·cm^{-2}·month^{-1})

latitude	first half-years					second half-years				
	Q_a	A_1	A_2	B	I_s	Q_a	A_1	A_2	B	I_s
80—90° C	7,8	4,5	0	—0,8	—11,5	0,1	9,1	0	0,8	—10,0
70—80	8,2	4,4	0	—0,8	—11,8	0,5	9,3	0	0,8	—10,6
60—70	11,5	1,8	0,4	—1,2	—12,5	1,8	6,7	1,5	1,2	—11,2
50—60	14,6	0,0	1,3	—2,8	—13,1	4,0	4,7	0,5	2,8	—12,0
40—50	16,9	—1,0	2,0	—3,9	—14,0	6,5	2,9	—0,6	3,9	—12,7
30—40	19,2	—1,4	1,7	—4,3	—15,2	9,5	0,9	—0,7	4,3	—14,0
20—30	20,0	—2,0	0,4	—2,9	—15,5	13,7	—0,9	—0,6	2,9	—15,1
10—20	19,7	—2,4	—0,9	—1,4	—15,0	17,0	—1,8	—1,0	1,4	—15,6
0—10	18,4	—1,4	—2,2	0,1	—14,9	18,7	—2,1	—1,4	—0,1	—15,1
0—10° Ю	18,0	—2,3	—2,2	1,5	—15,0	19,7	—2,4	—0,8	—1,5	—15,0
10—20	16,2	—2,6	—0,9	2,5	—15,2	20,7	—3,5	0,3	—2,5	—15,0
20—30	13,0	—1,4	—0,3	3,4	—14,7	20,6	—3,5	1,2	—3,4	—14,9
30—40	8,9	0,4	0,4	4,2	—15,9	18,9	—2,0	1,4	—4,2	—11,1
40—50	5,9	1,9	1,6	3,5	—12,9	15,9	0,0	0,6	—3,5	—13,0
50—60	3,3	3,9	2,6	2,5	—12,3	12,8	2,6	—0,6	—2,5	—12,3
60—70	1,0	9,5	0	0,8	—11,3	8,1	4,3	0	—0,8	—11,6
70—80	0,2	9,8	0	0	—10,0	4,4	6,5	0	0	—10,9
80—90	0,0	8,8	0	0	—8,8	3,4	6,9	0	0	—10,3

The upper half of the left side of the table and the lower half of the right side refer to the warm half of the year, the lower half of the left side and the upper half of the right side, to the cold half of the year. /15

From the table being considered it is evident that the absorbed radiation is not the only factor determining the magnitude of the outgoing radiation. For the temperature and high latitudes during the cold half of the year (for high latitudes of the southern hemisphere during the whole year) the main source of heat is its transfer from the lower latitudes by the atmospheric circulation.

Of the two processes of heat exchange in the oceans, the more significant is the seasonal buildup and dissipation of heat in the mass of oceanic waters. In several latitudinal zones the magnitude of this component of the heat balance reaches 25 -

*Commas in the table are to be understood as decimal points.

30% of the magnitude of the outgoing radiation. The redistribution of heat by ocean currents plays a smaller role, although in certain belts its magnitude can reach 15 - 20% of the radiation to outer space. It is important to note that the values of the components of the heat balance of the ocean being considered were referred to a common area of the latutudinal belts (in the majority of cases this noticeably decreases their magnitude in comparison with components of the heat balance referred to the area covered by the oceans).

The data of Table 1 show that for the determination of the outgoing radiation through other components of the heat balance it is necessary to take into consideration all the components of the balance included in the table.

Thus, numerical models of the thermal regime of the atmosphere which include an accounting of the influence on outgoing radiation of only the absorption of solar radiation can always provide inaccurate results in the study of changes of air temperature in various latitudinal belts. The construction of a closed numerical model of the thermal regime, including an account of all the basic components of the heat balance of the earth-atmosphere system, is associated with large difficulties, which at the present are succeeding in being overcome mainly by strong schematization of the process being studied. One of the methods of such schematicization is incorporated in the construction of a semiempirical theory of climate. Among them belong models worked out at the Main Geophysical Observatory (Budyko, 1968; Budyko, Vasishcheva, 1971), and likewise models proposed by American authors (Sellers, 1969; Faegre, 1972).

Starting with our 1968 work, all models proposed for the indicated research include an accounting of the inverse relation between the thermal regime of the atmosphere and polar ice, which has significant value in the study of the stability of the contemporary climate. The essence of this inverse relation is contained in the following.

As was shown by observation with meteorological satellites of /16 the earth, the albedo of the earth-atmosphere system in the polar ice regions is significantly greater than the albedo of ice-free regions. As a result of this, during the period of contraction of the area of polar ice induced by warming, the magnitude of the absorption of radiation is increased, which can promote further raising of the temperature. At the time of an increase in the ice area as a result of cooling, an increase in albedo can lead to additional decrease of temperature.

Taking into consideration this inverse relation, it was possible to obtain a conclusion on the very great sensitivity of contemporary climatic conditions to small changes in the climate-producing factors. Thus, in particular, it was made clear that a decrease in the flux of solar radiation by an amount of around 2% can lead to the complete glaciation of the terrestrial sphere (Budyko, 1968).

A similar condlusion was obtain also in the works of Sellers and Faegre. Another conclusion deserves attention, which proceeds from the semiempirical models of the thermal regime of the atmosphere, namely the conclusion of a nonunique relation between contemporary climate and external climate-producing factors. This conclusion was first obtained as a result of calculation of the thermal conditions for a "white earth," i.e., for the case of complete glaciation of our planet. From simple physical considerations it follows that with the present magnitude of the solar constant and complete glaciation of the earth, the temperature of the earth's surface would be equal to several tens of degrees below zero, ensuring great stability of the regime of glaciation (Budyko, 1962). This conclusion was likewise reached from the model of the thermal regime of the atmosphere mentioned above (Budyko, 1968). By means of this model the distribution of average latitudinal temperatures was calculated for a "white earth", which turned out to vary from $-68^{\circ}C$ at the equator to $-73^{\circ}C$ at the pole (Budyko, 1971). It is important to note that, although the corresponding values of temperature signfiicantly depend on the choice of the magnitude of the albedo for an ice-covered earth's surface, for any plausible values of the albedo the middle-latitude temperatures remain considerably below zero. Thus, a "white earth" is the second possible version of the climate for contemporary conditions.

From a model of the thermal regime which we proposed the conclusion was also drawn that the existence of a third version of the climate was possible, namely, with partial glatiation of the earth and with lower temperatures compared with the present. However, this version of the climatic regime is unstable, i.e., it transforms to other markedly different types of climatic conditions with very small changes in the climate-producing factors (Budyko, 1972).

In the work of Faegre mentioned above the use of the semiempirical model of the thermal regime of the atmosphere proposed by him resulted in five differing solutions, of which Faegre considered three to have physical meaning - a distribution /17
of temperature corresponding to contemporary climatic conditions, a distribution of temperature for the case of complete glaciation of the earth, and a distribution with partial glaciation and with average temperatures lower by comparison with those existing. Although Faegre supposed that obtaining a conclusion for the

possibility of existence of three climatic regimes for the present value of the solar constant is a peculiarity of the model which he worked out, it is nevertheless clear that differing semiempirical models lead to one and the same conclusion about the ambiguous connection of the earth's climate with climate-producing factors.

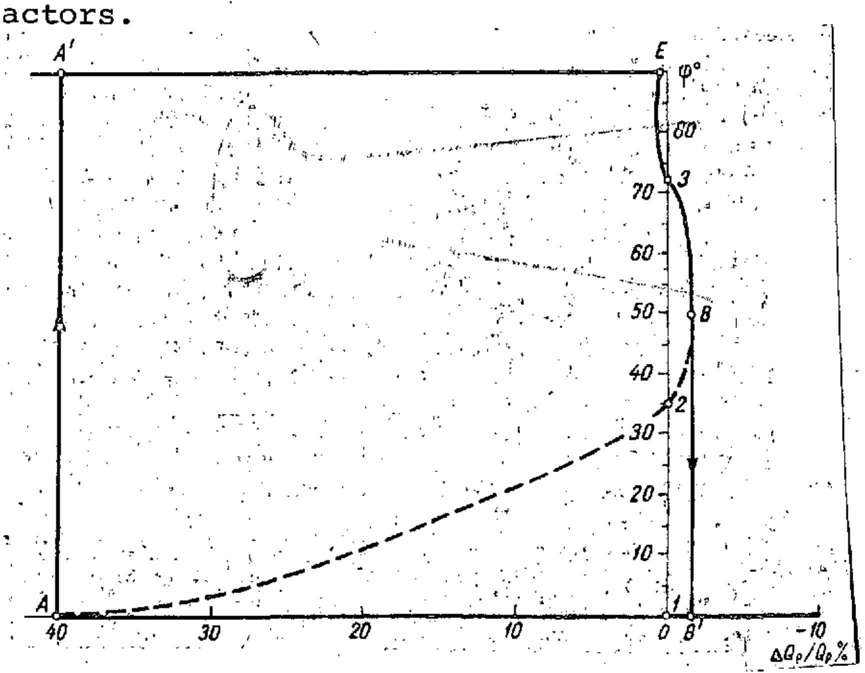

Fig. 1. Dependence of the average latitude of the boundary of the polar ice cover in the Northern Hemisphere on the influx of radiation at the outer limit of the atmosphere.

We shall now consider the question of the sensitivity of the contemporary climate to slight changes in the climate-producing factors. Using the model proposed earlier for the calculation of the distribution of the average annual value of the average latitudinal air temperature at the earth's surface (Budyko, 1968), one can find the dependence of the boundary of polar ice in the Northern Hemisphere on the magnitude of the solar constant.

This dependence is presented in Fig. 1, where $\Delta Q_p/Q_p$ is the relative change of influx of solar radiation at the outer limit of the atmosphere, expressed in percent, ϕ , the average latitude of the boundary of polar ice cover in the Northern Hemisphere.

The dependence of ϕ on $\Delta Q_p/Q_p$ is illustrated in the form /18
of a system of heavy lines which show that this relation has an ambiguous character and that it actually is different for cases of increasing and decreasing influx of heat at the outer boundary of the atmosphere. We shall first consider the case of an increase of the heat flow from an initially small value. In the case of small heat inflows (i.e., for $\Delta Q_p/Q_p$ numerically less than 0) complete glaciation of the earth takes place ($\phi = 0^{\circ}$) which lasts during the increase of the heat flow to its present value (point 1), and up to a value exceeding the indicated value by several tens of percent (point A). The regime of glaciation corresponding to point A is unstable and with a slight increase of the heat flux transforms to a regime of complete absence of glaciation (point A'). Further increase of the heat flux corresponds to the preservation of an ice-free regime.

With a decrease of the heat flux from an initial value significantly exceeding the solar constant, conditions of an ice-free regime ($\phi = 90^{\circ}$) are observed at first. On reaching point E, close to the contemporary value of the heat flux, polar glaciation appears, which rapidly increases with decrease of heat flux. After reaching point 3, corresponding to the present climatic regime, with a decrease of the influx of heat by a value about 2% of that now observed, the ice cover reaches 50° North latitude (point B).

The regime of glaciation corresponding to this point is unstable and with slight decrease in the heat influx transforms to a regime of complete glaciation (point B'), which is maintained with further lowering of the heat flux.

Using the model mentioned above it is also possible to get the relation between the quantity ϕ and $\Delta Q_p/Q_p$, illustrated by the dashed curve AB. Since for this curve there is typically an increase in the value of ϕ with a decrease in $\Delta Q_p/Q_p$ (or a decrease in ϕ with an increase in $\Delta Q_p/Q_p$), one may suppose that it corresponds to an unstable regime of glaciation that transforms to a regime of complete glaciation or complete absence of glaciation with small fluctuations in the heat flow. Regarding that point on curve AB corresponding to the present value of the heat flux (point 2), it characterizes an unstable regime, which cannot exist for a long period.

Thus the dependence of polar glaciation on heat flow has the form of a hysteresis loop, the segments AA' and BB' of which refer to conditions of increasing and decreasing influx of heat, which are shown in Fig. 1 by arrows.

The other segments of the hysteresis loop, corresponding to unstable regimes of glaciation, can characterize the dependence of ϕ on $\Delta Q_p/Q_p$ in the cases of both increase and decrease of the heat flow.

A more complex model of the thermal regime of the various seasons can likewise be used for the study of the dependence presented in Fig. 1 (Budyko, Vasishcheva, 1971). Application of this model gives results differing somewhat in quantitative /19 relation from the scheme illustrated in Fig. 1, but completely agreeing with the relations of the basic qualitative mechanisms which we are considering.

This result seems natural, inasmuch as one must establish these mechanisms on the basis of general considerations which it is necessary to take into account during development of the most different models of the thermal regime (Budyko, 1972).

Thus, it is probable that the hysteresis character of the

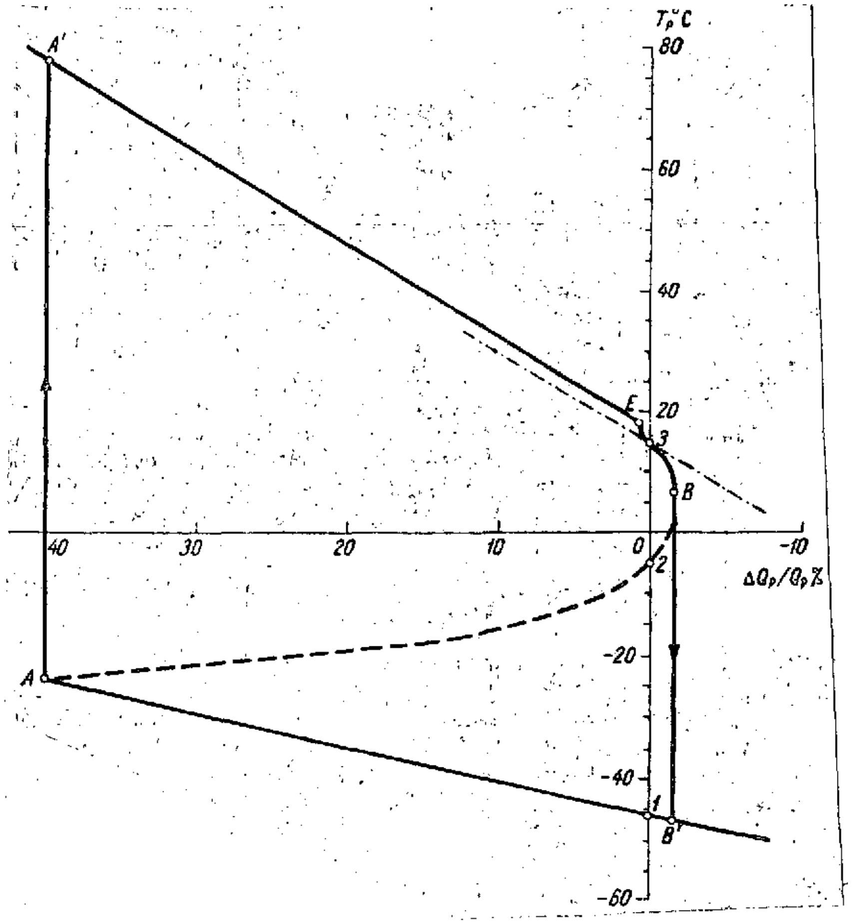

Fig. 2. Dependence of the average planetary temperature $T_{\hat{p}}$ on the influx of radiation at the outer boundary of the atmosphere $\Delta Q_p/Q_p$.

dependence of polar glaciations on the heat influx will be supported by further investigations, based on the application of more complicated models of the thermal regime of the atmosphere.

The dependence of the average planetary air temperature at the earth's surface on the heat flux, determined with the aid of the models described above, is presented in Fig. 2. All markings in this figure agree with those accepted in Fig. 1. /20

As is evident in Fig. 2, the dependence of the average planetary temperature on the heat influx is in many ways analogous to the corresponding dependence for the limit of polar glaciation and likewise the character of a hysteresis loop.

The immense drop of temperature for "white earth" conditions, i.e., for complete glaciation, deserves attention. The question of the thermal regime of a "white earth" is considered in more detail below.

The actual changes of temperature during the major part of the earth's history was evidently limited by the small line segment, distinguishing possible thermal regimes of our planet from values located a little higher than point E down to magnitudes lying slighly above point B. Comparison is interesting of that portion of the line being considered with the dot-and-dash straight line drawn through point 3 and corresponding to changes in the average planetary temperature in the absence of an influence of polar ice on the thermal regime. Such comparison indicates how polar ice intensifies changes of temperature due to fluctuations of heat inflow.

4. THE INFLUENCE OF ATMOSPHERIC CARBON DIOXIDE ON THE THERMAL REGIME

For the elucidation of the possible influence of changes of carbon dioxide concentration on climatic conditions, the study of the climatic regimes related to the section BE of the curves presented in Figs. 1 and 2 have the greatest significance.

Especially characteristic of these regimes is their high sensitivity to changes of heat inflow, in connection with which climatic conditions can be significantly changed with comparatively small fluctuations in climate-producing factors.

Using the model of the thermal regime of the atmosphere mentioned above one can evaluate approximately how changes in carbon dioxide concentration affects the average planetary temperature at the earth's surface.

We shall assume that in the absence of an inverse relation between air temperature and polar ice the temperature at the earth's surface would change with fluctuations in carbon dioxide concentration in accordance with the dependence established in the work of L. R. Rakipova and O. N. Vishnyakova mentioned above.

For the estimation of the influence of carbon dioxide concentration on the thermal regime, taking into account the indicated inverse relation, we shall make use of the relationship

$$I'_s = \gamma I_s \tag{1}$$

(I_s is the long wave radiation going to outer space with the contemporary value of the carbon dioxide concentration in the atmosphere, I'_s, the outgoing radiation for various values of the carbon dioxide concentration, γ, a dimensionless coefficient depending upon the carbon dioxide gas concentration), which one can take to be sufficiently accurate for small differences of the coefficient γ from 1. /21

Using for the determination of I_s an empirical relationship established in work completed earlier (Budyko, 1968 et al.), we find

$$I_s = \gamma \left[a + bT - (a_1 + b_1 T)\, n\right], \tag{2}$$

where T is the air temperature at the earth's surface in degrees Celsius, n, cloudiness in fractions of unity, a, b, a_1, and b_1, dimensionless coefficients.

Taking into consideration that for the terrestrial sphere as a whole the quantity of absorbed radiation is equal to the outgoing radiation, we obtain the relationship

$$Q_p(1-\alpha_p)=\gamma\,[a+bT_p-(a_1+b_1T_p)\,n_p]. \tag{3}$$

Here Q_p is the solar radiation at the outer boundary of the atmosphere, α_p, the albedo of the earth-atmosphere system, T_p, the average planetary temperature at the earth's surface, n_p, the average cloudiness. From this we find the formula for the determination of the average planetary temperature

$$T_p=\frac{Q(1-\alpha_p)-\gamma a+\gamma a_1 n_p}{\gamma(b-b_1 n_p)}. \tag{4}$$

We shall suppose that the coefficient δ depends slightly on latitude. In this case, employing the semiempirical theory of the thermal regime of the atmosphere (Budyko, 1968) for the determination of the average annual temperature in the different latitudinal belts, we obtain the formula

$$T=\frac{Q(1-\alpha)-\gamma a+\gamma a_1 n+\beta T_p}{\beta+\gamma b-\gamma b_1 n}, \tag{5}$$

where Q, δ, n, and T refer to the latitudinal belt being considered, β is a dimensional coefficient characterizing the intensity of the meridional heat exchange.

The value of the coefficient δ for various carbon dioxide concentrations can be found from equation (3), using it jointly with the relationship established by L. R. Rakipova and O. N. Vishnyakova and presented in Fig. 3 in the form of a dashed line.

Taking into consideration these values, and allowing for the connections established earlier of the limit of polar ice cover and the albedo with the air temperature (Budyko, 1968), one can calculate how the average planetary temperature is changed as a result of changes in carbon dioxide concentration in the presence of an inverse connection between polar ice and the thermal regime. The result of this computation is presented in Fig. 3 in the form of a continuous line.

/22

As is evident from Fig. 3, a change in the area of polar ice markedly intensifies the influence of fluctuations of carbon dioxide concentration on the average planetary temperature. With an increase in the carbon dioxide concentration by 30% relative to tis present-day level, the temperature notably increases, and, for a carbon dioxide content greater than 0.05%, becomes higher by 4 - 5^{o} than the temperature existing now.

With a decrease in the quantity of carbon dioxide the average planetary tmeperature falls, the average temperature at the

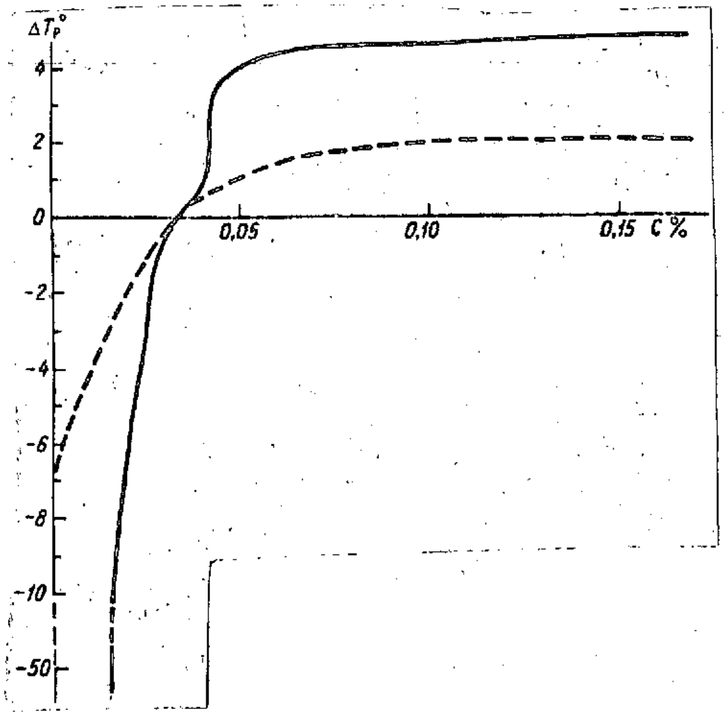

Fig. 3. Dependence of changes of average planetary temperature ΔT_p on carbon dioxide concentration C.

earth's surface falling several tens of degrees for a carbon dioxide concentration equal roughly to half of its contemporary value, which corresponds to conditions of complete glaciation of the earth.

The dependence of the boundary of polar ice in the Northern Hemisphere on the quantity of carbon dioxide during its decrease, calculated by the scheme presented, is depicted in Fig. 4. An increase in carbon dioxide concentration of 30% by comparison with its contemporary value appears sufficient for the complete thawing of the polar ice, and a reduction in the concentration by a factor of 2 leads, as noted above, to the complete glaciation of our planet.

In considering the dependences presented in Figs. 3 and 4, one must keep in mind that they characterize steady-state conditions of the atmosphere - ocean - polar ice system, which can be attained only after a long interval of time, on the order of thousands of years. If the changes in carbon dioxide concentration take place significantly more rapidly (as is taking place, /23 for example, in the modern epoch), changes of thermal regime and the polar ice limit will be notably smaller than those changes which are determined by the relationships presented in Figs. 3 and 4. The question of the computation of the influence of such relatively rapid changes of carbon dioxide concentration on climate was considered in one of our earlier completed works (Budyko, 1972).

With the aid of equations (4) and (5) one can calculate the distribution of average latitudinal temperature at the earth's surface for an ice-free regime, corresponding to a concentration of carbon dioxide gas equal to 0.042%, and for complete glaciation of the earth, corresponding to a concentration of carbon dioxide gas equal to 0.015%.

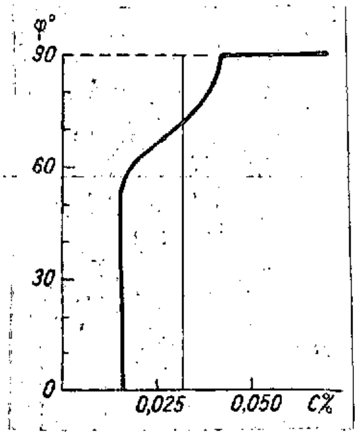

Fig. 4. Dependence of average latitudinal limit of polar ice cover in the Northern Hemisphere on the concentration of carbon dioxide gas.

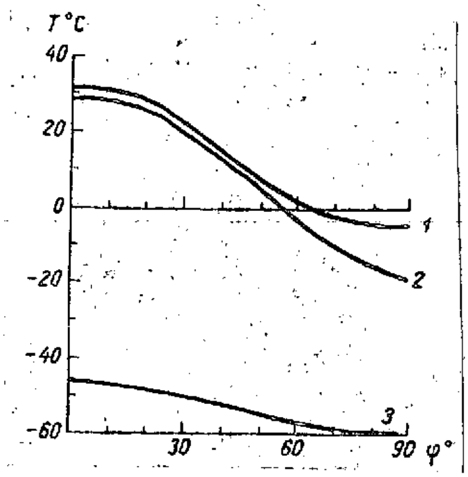

Fig. 5. Distribution of average latitudinal temperature in the Northern Hemisphere with concentration of carbon dioxide gas equal to 0.042% (1), for the contemporary regime (2), and for concentration of carbon dioxide gas equal to 0.015% (3).

The computation for the first case was made assuming that the albedo of the earth-atmosphere system at high latitudes in the absence of ice is equal to 0.40. In the computation the influence on the thermal regime of possible changes in cloudiness is disregarded.

In the second computation it is assumed that the albedo is equal to 0.64 at all latitudes, and that the influence of the cloud-cover on the thermal regime is insignificant.

The results of computation for the Northern Hemisphere are presented in Fig. 5 in the form of curve 1 (ice-free regime) and curve 3 (complete glaciation of the earth). The distribution of average latitudinal temperature for contemporary climatic conditions are illustrated by curve 2.

As is obvious from the figure, with a rise in carbon dioxide concentration to 0.042% the average annual temperature in the low latitudes incrases approximately 2°, and in the high latitudes up to 11°.

In the case of complete glaciation ("white earth") the average annual temperature drops by roughly 70° at the equator and by roughly 45° at the pole. It is important to note that the temperature values found in this computation for conditions of complete glaciation differ somewhat from the values obtained in a former work (Budyko, 1971). This difference is explained by the use in the computation presented of the natural assumption that the influence of cloudiness on the thermal regime is insignificant at very low air temperatures, and also by the employment of a somewhat smaller value of albedo for a "white earth." /24

Thus, as a result of the immense influence of the inverse relation between the thermal regime of the atmosphere and polar ice on the distribution of air temperature, relatively small changes of carbon dioxide concentration, from 0.015 to 0.042%, modify the average annual air temperature in various latitudinal belts by several tens of degrees.

Although the accuracy of this computation is limited in connection with the presence in the model of the thermal regime used of a series of simplifying assumptions (these assumptions are discussed in a preceding work - Budyko, 1972), one can believe that the conclusion about the lowering of the air temperature by several tens of degrees with complete glaciation of the planet will not be changed with the application of more detailed models of the thermal regime (this conclusion is supported in particular by the works of Sellers and Faegre mentioned above.).

At the same time the estimate derived here of the change in concentration of carbon dioxide will bring about complete glaciation has a very approximate character and must be refined in future investigations.

5. THE FUTURE OF THE BIOSPHERE

We shall close with the question of the possibility of using the dependence of climatic conditions on the carbon dioxide concentration found here for the study of the mechanisms of natural changes of climate which proceed relatively slowly.

As is evident in Figs. 3 and 4, the influence of the quantity of carbon dioxide in the atmosphere on climate appears most remarkable relative to the narrow range of its concentration - from 0.015 to 0.042%. For higher and lower concentrations the influence of carbon dioxide on the thermal regime is less significant. Within this narrow range slight fluctuations in the quantity of carbon dioxide can bring about immense changes of the thermal regime.

One can think that the dependences presented in Figs. 3 and 4 characterize conditions of the last millions of years of geological history, when the location of the continents and oceans differed little from the present. In this connection, it is obviously impossible to make use of these dependencies for the study of the genesis of ancient pre-Quaternary glaciations. As for periods closer to our time, one can suppose the presence of a definite connection between the considerable cooling which occurred at the end of the Pleocene to the beginning of the Pleistocene and the diminution of carbon dioxide in the atmosphere. /25

According to available data, at the start of the rise in carbon dioxide concentration that took place in recent decades its value amounted to about 0.029% (Inadvertent Climate Modification, 1972). This magnitude is smaller by 0.013% than the critical magnitude at which polar glaciation must have occurred. A change of carbon dioxide concentration by 0.013% using the estimate of the rate of its decrease for the last 200 million years presented above could have occurred in approximately 300 thousand years, which, in order of magnitude, agrees with the duration of the Quaternary period. It is understandable that it is impossible to obtain more precise agreement in the present case because of significant inaccuracy of the magnitude of the average rate of decrease in the quantity of carbon dioxide, and because this rate in the last millions of years obviously decreased.

The question deserves attention as to whether the fluctuations in carbon dioxide concentration in the Quaternary period could have brought about the advance and retreat of the ice cover.

From Fig. 4 it is evident that the limits of polar glaciation are displaced by 5 - 10° with changes in concentration of carbon dioxide by 0.005 - 0.010% in all, i.e. by 1/6 - 1/3 of its present-day content. While such changes are relatively small, there exists no data that they actually took place during the epoch of development and diminution of glaciation.

In contrast, there is no doubt that in the Quaternary period the location of the earth's surface relative to the sun periodically changed. Inasmuch as computations carried out show that changes in the radiation regime connected with this cause were sufficient for the development of glaciation (Budyko, 1972), one can think that the fluctuations of the carbon dioxide concentration (as well as changes in atmospheric transmissivity due to volcanic activity) had small influence on glaciation.

Along with this, as noted above, it is always possible that the gradual lowering of the carbon dioxide concentration was the essential factor making possible the development of glaciation.

Changes of the location of the earth's surface relative to the sun did take place both in Mesozoic and Tertiary time, but they did not bring about the occurrence of important glaciation.

In a series of investigations the assumption was asserted that the absence of glaciation during this epoch was connected with an increased intensity of meridional heat exchange due to a different location of the continents more conducive to the development of ocean currents which transported heat from low latitudes to high.

In our previous works it was remarked (Budyko, 1971) that such a proposition was entirely credible, but it did not explain the considerable lowering of the average planetary temperature which occurred at the end of Tertiary era. One can think that the cooling during this epoch was connected with the decrease /26 of carbon dioxide concentration in the atmosphere below the critical value indicated above, following which considerable polar glaciations appeared, the dimensions of which grew with a reduction in the arrival of radiation at the high latitudes in the warm part of the year.

The evolution of polar ice covers in the future must depend essentially on changes of carbon dioxide content in the atmosphere.

At the beginning of this work it was remarked that, for a long time, there existed a tendency for the lowering of the concentration of atmospheric carbon dioxide. One may think that changes of the amount of free carbon dioxide in the atmosphere and hydrosphere over a long period of time cannot depend on the increase or decrease of the total mass of living organisms. Thus, for example, if we would compute the total mass of living organisms corresponding to the value presented at the beginning of this work, a change of its magnitude by 100% can be compensated for by the arrival of carbon dioxide from the lithosphere (or the consumption of carbon dioxide in geological processes) for roughly ten thousand years. If it is assumed that in the past the quantity of biomass was larger by an order of magnitude, then the corresponding estimate would rise only to a hundred thousand years, i.e., to a magnitude still small by comparison with the duration of geological periods.

It is obvious that the influence of changes in the mass of living organisms on the carbon dioxide balance is negligible compared with the gas exchange of the atmosphere and lithosphere during long time intervals comparable with the geological periods.

In contrast to living organisms, the lithosphere can accumulate a very large quantity of carbon, and likewise consume a larger quantity of carbon dioxide over a long period of time. Therefore the geological components of the carbon dioxide balance, much smaller in magnitude than the biological components of the balance, have a basic significance for changes in the quantity of free carbon dioxide. In contrast to the biological cycle of carbon dioxide, in which the supply and consumption is practically balanced due to a relatively small mass of living organisms, the supply and consumption of carbon dioxide in the geological cycle is weakly connected with it. Therefore, occasions are possible when the supply of carbon dioxide from the lithosphere considerably exceeds its absorption by the lithosphere, and vice versa.

Computing that in contemporary conditions there is an order of magnitude difference in the consumption of carbon dioxide

as a result of geological processes and the arrival of carbon dioxide from the lithosphere equal to 10^8 tons/year, we find that the rate of change of the quantity of free carbon dioxide in the atmosphere and hydrosphere can amount to 10^{14} tons over a million years. Assuming that the quantity of atmospheric carbon dioxide amounts to 2% of the carbon dioxide in the hydrosphere, we obtain a possible magnitude of decrease of the quantity of atmospheric carbon dioxide over a million years equal to $2 \cdot 10^{12}$ tons, or 0.03%, which corresponds in order of magnitude to the estimate presented above of the average rate of decrease in /27
atmospheric carbon dioxide over the last 200 million years.

In this manner geological processes can be the cause of the changes in concentration of atmospheric carbon dioxide which are occurring. Quantitative analysis of the influence of processes in the lithosphere on the balance of carbon dioxide is hampered by the very low accuracy of the available information about the carbon balance in the lithosphere. Available estimates essentially permit determination of only an order of magnitude of the size of the corresponding members of the balance of atmospheric carbon dioxide, which is insufficient for the estimate of its possible changes in the future.

It was remarked above that with the results obtained in this work it is possible to find the changes in concentration of atmospheric carbon dioxide over time, occurring after the appearance of polar glaciations. This change comprises roughly 50% of the magnitude of carbon dioxide concentration which was observed in the contemporary epoch at the beginning of its rise under the influence of the industrial activity of man. Reckoning that the polar glaciations significant in area arose about a million years ago we find that the rate of reduction in concentration of carbon dioxide amounted to about 0.013% over a million years. This value is three times smaller than the estimate presented above of the average rate of decrease of carbon dioxide concentration in the atmosphere over the last 200 million years.

Such a difference appears natural, inasmuch as with the decrease of concentration of carbon dioxide the rate of its decrease, expressed in absolute units, likewise can decrease.

The question of the relation of the rate of absorption of carbon dioxide by the lithosphere to the levels of its concentration in the hydrosphere and atmosphere has great significance for the elucidation of the tendency of changes in the quantity of carbon dioxide in the future. If the rate of absorption would have been proportional to the concentration of carbon dioxide, the process of decrease in the quantity of carbon dioxide in the atmosphere and hydrosphere at its small concentrations would have been essentially retarded. However, there is a basis for believing that in several conditions the rate of absorption is not decreased with a lowering of the carbon dioxide concentration, but increases. Thus, in particular, A. B. Ronov calculated (Ronov, 1959) that the consumption of carbon dioxide inthe formation of sedimentary rocks in the oceans increases with the lowering of the carbon dioxide concentration, which increases the pH index of oceanic waters.

In the absence of a direct relation between the rate of absorption of carbon dioxide and its concentration, and all the more in the presence of an inverse connection between these magnitudes, the content of carbon dioxide gas in the atmosphere can drop comparatively rapidly to very small values.

For the elucidation of possible changes in the quantity of carbon dioxide in the atmosphere and hydrosphere an investigation of the carbon dioxide balance in detail is required, including a study of the connections between concentrations of carbon dioxide and various components of the balance. In the accomplishment of such an investigation for the estimate of the quantity of carbon dioxide in the future, it is necessary to be restricted by the extrapolation of available data on changes of concentrations /28 of atmospheric carbon dioxide during the latest geological period.

Employing such an extrapolation, one can estimate over what period the concentration of carbon dioxide in the atmosphere could have been reduced from its value which existed before the epoch of rapid industrial development, equal to 0.029%, to the magnitude at which complete glaciation of the planet is possible, equal to 0.015% by the data presented above. The difference between these two values is close to the change of carbon dioxide concentration which occurred over the period from the beginning of the Pleistocene to the contemporary epoch. In this manner one must conclude that the complete glaciation of the earth could have occurred over a period of time comparable with the duration of the Pleistocene, i.e., in approximately a million years.

If we take into consideration that, along with the general tendency in the development of glaciation, brought about by the lowering of the carbon dioxide concentration, there occurred periodic epochs of increase in ice cover due to change of the position of the earth's surface relative to the sun, then this value has to diminish. The probable time of onset of complete glaciation, taking into account the indicated effect, amounts to several hundred thousand years.

Accepting this evaluation, once can imagine the following picture of possible evolution of the biosphere.

A prolonged decrease in the concentration of carbon dioxide will be accompanied by the gradual reduction of the productivity of autotrophic plants and a reduction of the total mass of living organisms on earth. Simultaneously, the belt of polar glaciations will spread, which, with the apperance of an ice age, will be intermittent at the lower latitudes.

The productivity of autotrophic plants and the total volume of biomass on the earth will have decreased by not more than a factor of two when the ice cover reaches a critical latitude, after which it will spread right up to the equator in the sequence of its development. As a result the complete glaciation of the planet will occur, which will have great stability because of the low negative temperatures at all latitudes of the terrestrial sphere.

One can think that complete glaciation will lead to the cessation of all biological processes on our planet. This supposition is based on the fact that over the long period of existence of the Antarctic glacier no kinds of living organisms arose which could continually exist in the central regions of that glacier. With the extension for a comparatively short time of the climatic conditions of central Antarctica to the whole terrestrial globe it is hard to imagine the appearance of living organisms which could adapt to such unfavorable conditions.

The complete glaciation of the planet corresponding to the thermal regime noted in Fig. 2 by the point B' must be extraordinarily stable, since at all latitudes the air temperatures would be considerably lower than the freezing point of water. It is possible at the same time that the glaciation /29 indicated in the distant future might disappear as a result of the gradual increase of the solar constant.

As is well known, in a series of astronomical investigations the proposition was stated that, in the course of the evolution of the sun, the temperature of its surface and the quantity of energy emitted by it will increase. This effect could reach a considerable magnitude in several milliards (billions) of years (White, 1967).

As is evident in Fig. 2, an increase in the solar constant by roughly 40% is necessary for the destruction of a planetary glaciation. In such an event the ice would thaw at all latitudes and the air temperature would rise by more than 100°, reaching an average magnitude of about 80°C. Inasmuch as with the future increase of the solar constant the temperature of the earth's surface will continue to rise, it is doubtful whether the thawing of the ice will lead to the creation of conditions suitable for another genesis of life on earth.

Taking into account that the question of the future evolution of the sun is not entirely clear, it is important to notice the hypothetical character of this route of change of the thermal regime of the earth. It is interesting however, that in its realization the thermal regime will proceed along stages, corresponding in large part to the hysteresis curve in Fig. 2 - from the ice-free regimes of Mesozoic times (a little above point E) to contemporary conditions (point 3), conditions of complete glaciation (from point B' to A), and the destruction of the glaciation (point A').

The estimate presented above of the time during which complete glaciation of the planet could take place has, for a variety of reasons, a very approximate character. Along with the schematic nature of the model of the thermal regime of the atmosphere used for the determination of this appraisal, the accuracy of the completed calculation is significantly limited by the application of a method of determining the rate of decrease of the carbon dioxide content in the atmosphere which has a quite hypothetical character.

One can think that the result obtained here is interesting chiefly as an illustration of the proposition stated earlier concerning the specific nature of the Quaternary glaciations (Budyko, 1971). To us it seems possible that, in contrast to Permian-Carboniferous and other ancient glaciations, the Quaternary glaciations are not temporal episodes in the evolution of the earth, but the commencement of a transition from the stability of the ice-free climatic regime to the still more stable regime of complete glaciation of the planet. The duration of this transitional period, by which the existence of the biosphere could have ended, as follows from the estimate presented above, is very small compared with the total duration of the existence of life on our planet.

Accepting this point of view, it can be concluded that man appeared at a recent moment in the evolution of the biosphere.

The exceptionally rapid development from the point of view of geological time of a civilization of indigenous form has changed the outlook for the future existence of the biosphere.

The data presented above show that for the last decades, /30
as a result of the burning of various forms of fuel, the carbon dioxide concentration in the atmosphere increased by 0.003%. Such an increase in the quantity of atmospheric carbon dioxide compensates for its decrease which was accomplished over a time beyond two hundred thousand years. Thus, man's activity has changed the direction of the process of change of concentration of atmospheric carbon dioxide and its rate was increased by a thousand times.

Although in this given case the influence of man on climate had an indirect character, it has already acquired a not insignificant meaning for the prevention of the future development of glaciations.

Let us imagine the improbable case that, in the future, the influence of man on the atmosphere comes to a halt. It can be put forward that in such conditions the attainment in the last hundred years of an increase in the concentration of carbon dioxide in the atmosphere deferred the complete glaciation of the planet by a thousand years. It is obvious that with the maintenance of the present degree of influence on the atmosphere, and the more so with its increase, the possibility of a global glaciation will be eliminated.

The most up-to-date question connected with the increase in carbon dioxide content of the atmosphere in the contemporary epoch is contained in the evaluation of the influence of the relatively rapid changes of carbon dioxide concentration on climatic conditons. Data are available which indicate that such changes can already in several decades bring about considerable influence on the marine polar ice and on climatic conditions of the high and partly the temperate latitudes (Budyko, 1972).

There is great interest likewise, as to the question of the change in magnitude of photosynthesis with the future increase in the carbon dioxide concentration of the atmosphere. It is always possible that with the future increase in the quantity of carbon dioxide gas in the atmosphere and hydrosphere the productivity of autotrophic plants will increase, thereby enlarging the very energy base for all living organisms, including man.

The future study of these questions has great practical significance.

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